Regional Stratification and Shear of the Various Streams of the Philippine Seas

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LONG-TERM GOALS

To provide observations and analysis of the stratification and shear at sub-meso to meso-scales and to regional scales of the various streams that feed into and through the Philippine Archipelago complex; to determine their relationship to the regional ocean and monsoon forcing. These contribute to the "Characterization and Modeling of Archipelago Strait Dynamics" DRI [PhilEx] goal: to enhance our understanding of the oceanographic processes and features arising in and around straits, and improve our capability to predict the inherent spatial and temporal variability of these regions using models and advanced data assimilation techniques.

OBJECTIVES

To resolve the circulation and mixing within the Philippine Archipelago and neighboring seas [South China Sea, Sulu Sea and boundary with the open Pacific Ocean]. Features and processes of particular interest are those associated with the interaction of the mean and tidal currents with the strong seasonal forcing at regional and smaller scales, including the effects of the complex topography characteristic, passage constrictions and topographic sills of the Archipelago; the interaction of the interior seas of the Philippine Archipelago [Mindanao and Sibuyan Seas] with the larger scale dynamics; dense 'ventilating' overflow into isolated deep basins; the response of the circulation to highly textures wind stress curl patterns induced by the Archipelago configuration.

APPROACH

The stratification and circulation is revealed through an array of CTD/Lowered ADCP stations as well as underway data [notably the hull mounted ADCP, SST/SSS and surface chlorophyll]. These data are integrated with other observational data, including satellite sensing, moored instrumentation and model output, as needed to meet the DRI objectives. I collaborate with other DRI observationalists: Amy Ffield, Earth and Space Research: LADCP; Pierre Flament, University of Hawaii at Manoa: High frequency radio; Craig Lee, University of Washington: towed vehicles and Gliders; Janet Sprintall, Scripps Institution of Oceanography: ADCP moorings; Julie Pullen for comparison to the COAMPS output; and Cesar Villanoy and Laura David, both at the Institute of Marine Research at the University of the Philippines.

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14. ABSTRACT

To provide observations and analysis of the stratification and shear at sub-meso to meso-scales and to regional scales of the various streams that feed into and through the Philippine Archipelago complex; to determine their relationship to the regional ocean and monsoon forcing. These contribute to the ?Characterization and Modeling of Archipelago Strait Dynamics? DRI [PhilEx] goal: to enhance our understanding of the oceanographic processes and features arising in and around straits, and improve our capability to predict the inherent spatial and temporal variability of these regions using models and advanced data assimilation techniques.

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WORK COMPLETED

The Regional PhilEx cruise [RIOP-08] aboard R/V Melville was accomplished in January 2008. The general objective of RIOP08 was to obtain a regional view of the stratification and circulation of the Philippine seas during the winter monsoon [Figure 1].

The specific objectives of the Regional IOP 2008 cruise:

- to reoccupy select stations of the exploratory cruise of June 2007 for comparison of the winter monsoon to the summer monsoon conditions;
- to further explore PhilEx related findings of joint cruise and to investigate changes as the winter monsoon matures from time of the joint cruise to our regional cruise;
- to acquire a detailed view of the conditions in the area of the Mindoro and Panay Straits [in support of the Craig Lee process cruise in February 08];
- to 'check out' features in the circulation and stratification suggested by model output and satellite derived data products;
- to further investigate overflow into Sulu and Mindanao Seas, as well as overflow into the 'interior seas' of Philippine waters;
- to investigate ocean response to the sharp wind-curl patterns associated with wind/island effect.

During RIOP08 we obtained 153 CTD-Oxy-fluorometer/LADCP stations [Figures 2] as well as underway data along the track [Figure 1]. We repeated several stations of the exploratory cruise of June 2007 to contrast the winter and summer monsoon ocean stratification and circulation. We also repeated stations obtained during the joint cruise of November/December 2007 to investigate the evolution of the ocean response to the developing winter monsoon. We preformed 4 underway surveys in the Mindoro/Paney and in the adjacent South China Sea region for evaluation of the 3 km resolution Coupled Ocean/Atmosphere Mesoscale Prediction System, COAMPS model ocean and atmosphere predictions.

Closely spaced arrays of CTD/LADCP, with supporting multibeam topographic data and the suite of underwater surface and hull ADCP data, were carried out over the ADCP moorings in the Panay Strait [11° 16.74'N; 121° 55.464'E; 106-116; 149-151 sequence] and Mindoro Strait [11° 53.648'N, 121° 03.294'E; CTD 121-132 sequence] . Station 118 was ~1 nm from the Tablas ADCP mooring [12° 00.288'N; 121° 49.608'E] . Station 88 was obtained ~1 nm from the MP1 mooring at 12°49.668'N; 120°36.930'E, the northern end of Mindoro Strait.

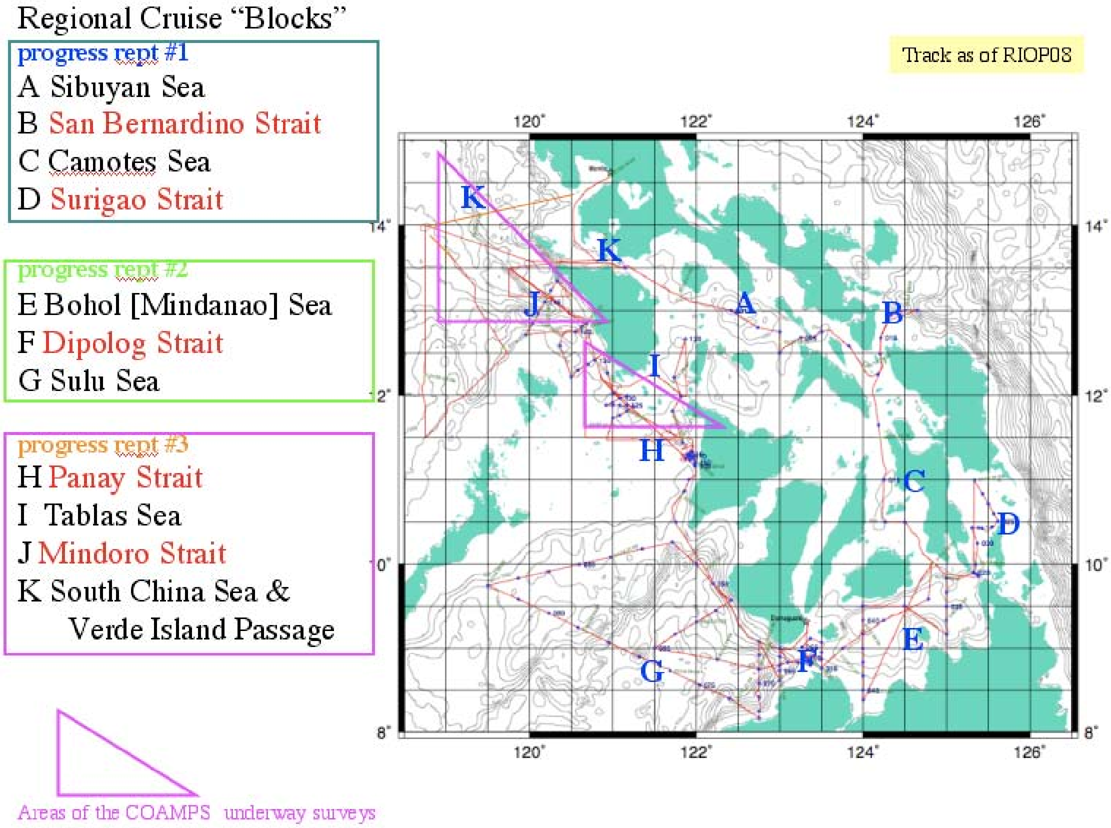

Figure 1 Research Blocks and ship track of RIOP08. The place names listed in the left panel are arranged by the weekly progress reports filed from the cruise.

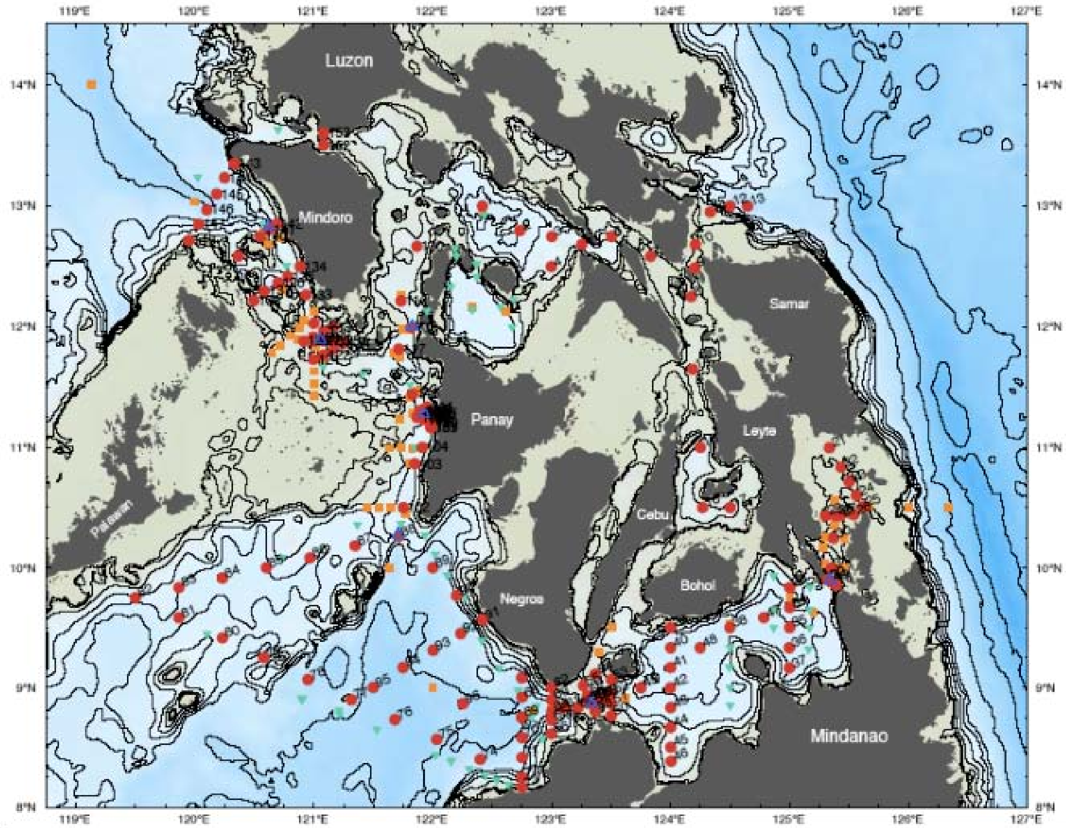

Figure 2 Regional 2008 IOP CTD/LADCP stations [red dots]. The smaller orange squares are stations obtained during the Exploratory Cruise June/July 2007. The green triangles are the stations of the Joint Cruise Nov/Dec 2007. The blue open triangles mark the positions of the ADCP and MP moorings.

RESULTS

The data from the three [Exploratory, June 2007; Joint, December 2007; Regional, January 2008] PhilEx cruises will be fully analyzed in an integrated fashion with the other PhilEx data sets during the Analysis phase of the DRI. Here are some preliminary results developed in the fy08 period:

• Regional Stratification: The group θ/S scatter, providing a view of the water mass stratification of the Philippine seas during the three PhilEx cruises [Figure 3]. There are some important differences between the June/July 07 Exp Cru and the RIOP-08, with the Joint cruise data showing transition into winter stratification and circulation conditions. An obvious difference is the increased freshwater inventory in January 2008 down to roughly 130 m throughout the region.

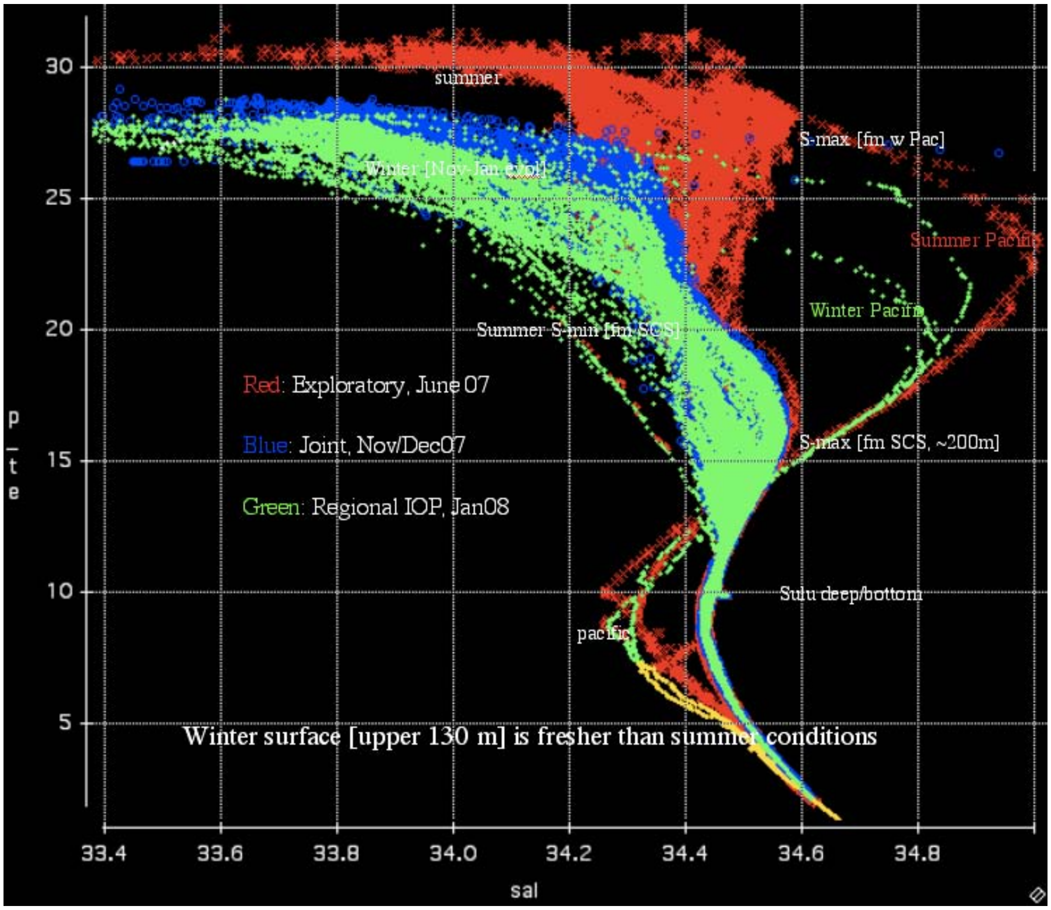

Figure 3 θ/S scatter for the Exploratory, Joint and Regional IOP08 PhilEx cruises

• Large Scale Surface Layer Circulation: Surface layer circulation from the hull ADCP, 150 KHz [Figure 4a,b] reveals the general pattern of surface circulation. The flow in the San Bernandino and Surigao Straits where strong tidal currents are found may mask the non-tidal flow, so caution is suggested in interpreting these vectors as vigorous mean flow of Pacific water into the interior Philippine seas. The January surface circulation in the Sulu Sea is cyclonic, whereas the gyre was anti-cyclonic in June 07. The January circulation is richer in meso-scale activity. In the Mindoro and Panay Straits the January currents form energetic eddies, a response to the complex wind stress curl, in June the surface flow was weak, towards the South China Sea. The deeper flow in both seasons is towards the Sulu Sea, feeding the gravity current overflow into the deep Sulu Sea.

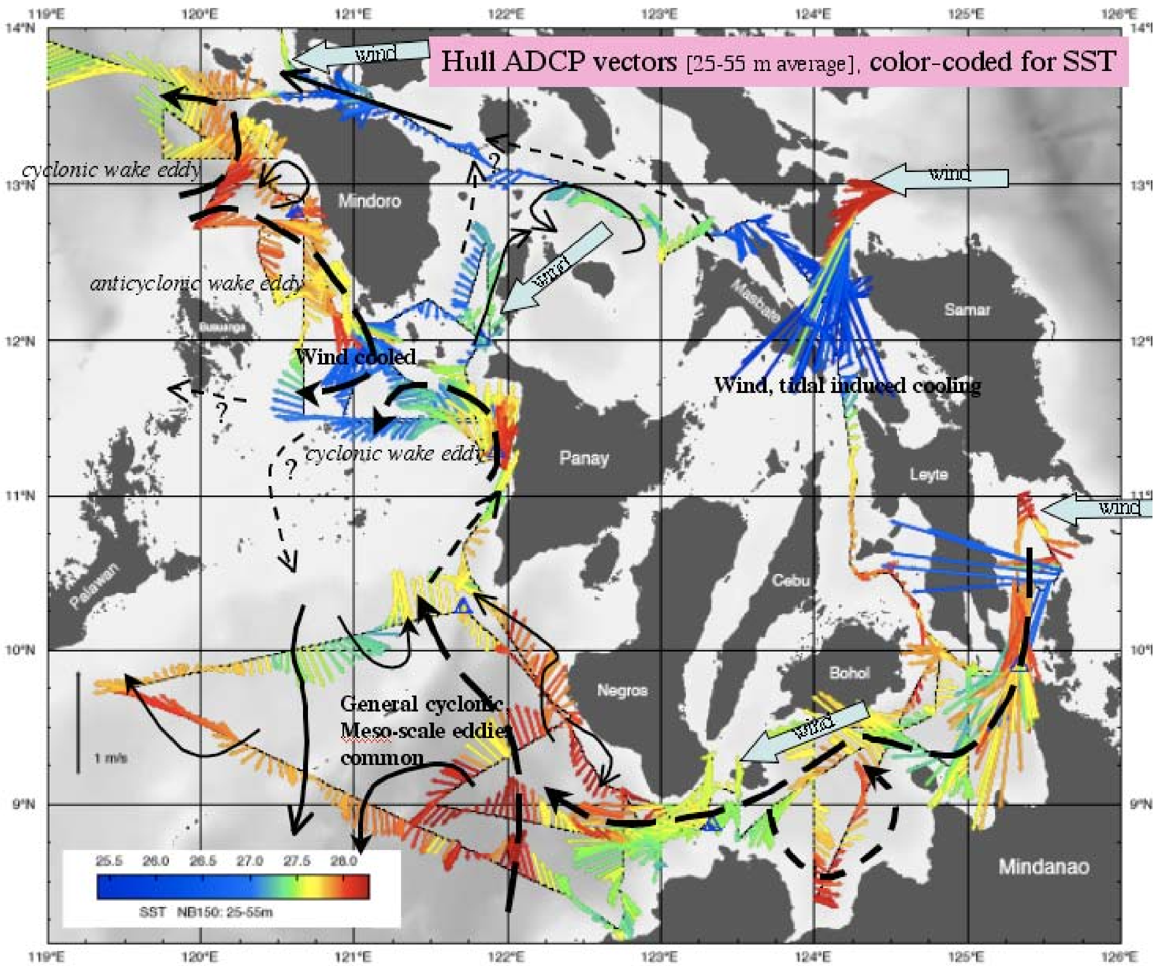

Figure 4a. Underway Hull ADCP derived currents, averaged in the 25-55 m interval, color-coded by SST along the path of RIOP08. The black arrows show suggested circulation features, with question marks added where the source or fate of the measured flow is uncertain.

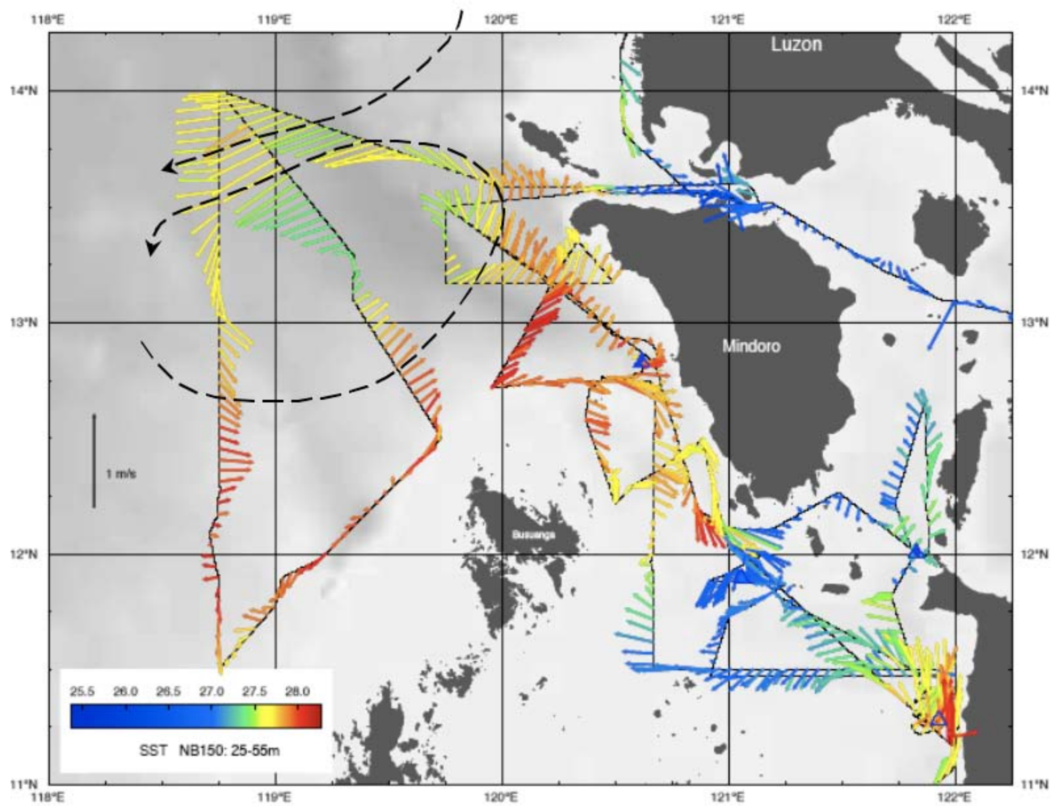

Figure 4b View of the hull ADCP 25-55 m average along the Mindoro and Panay tracks. Inferred circulation arrows are added to the large cyclonic eddy west of Mindoro. The ship line from 14N 118› 45'E to Manila will be added after the arrival in Manila.

• Pervasive O_2-min: From 12-14°C, 250-350 m, within the Philippine waters [excluding the western Pacific and South China Sea] there is an oxygen minimum. Its source is the displaced deep water of the isolated basins of the Mindanao and Sibuyan Seas [see figure 1 for place names]. These waters are forced out as shallower water ventilates the deep/bottom layers. Mindanao Sea presumably as it's the largest interior sea, is the primary source of the regional pervasive O_2-min stratum. The O_2-min water derived from the Sibuyan Sea is also observed in this layer, but its spatial reach is limited. The pervasive O_2-min is a convenient tracer of the regional subsurface flow.

• Stratification and Circulation within the Mindoro and Panay Straits:

§ Overflow into topographic depressions within the Mindoro and Panay Straits: Three topographic sills are encountered between the South China Sea and the Sulu Sea. Basin scale effective sill depth is less than the deepest connecting level due to the mixing, and the form of passage cross-section at the sill. For sills 2 and 3 shown in Figure 5 the difference is 120 and 175 m, respectively. This suggests fairly strong mixing of the benthic layer at the sills within the Mindoro and Panay Straits.

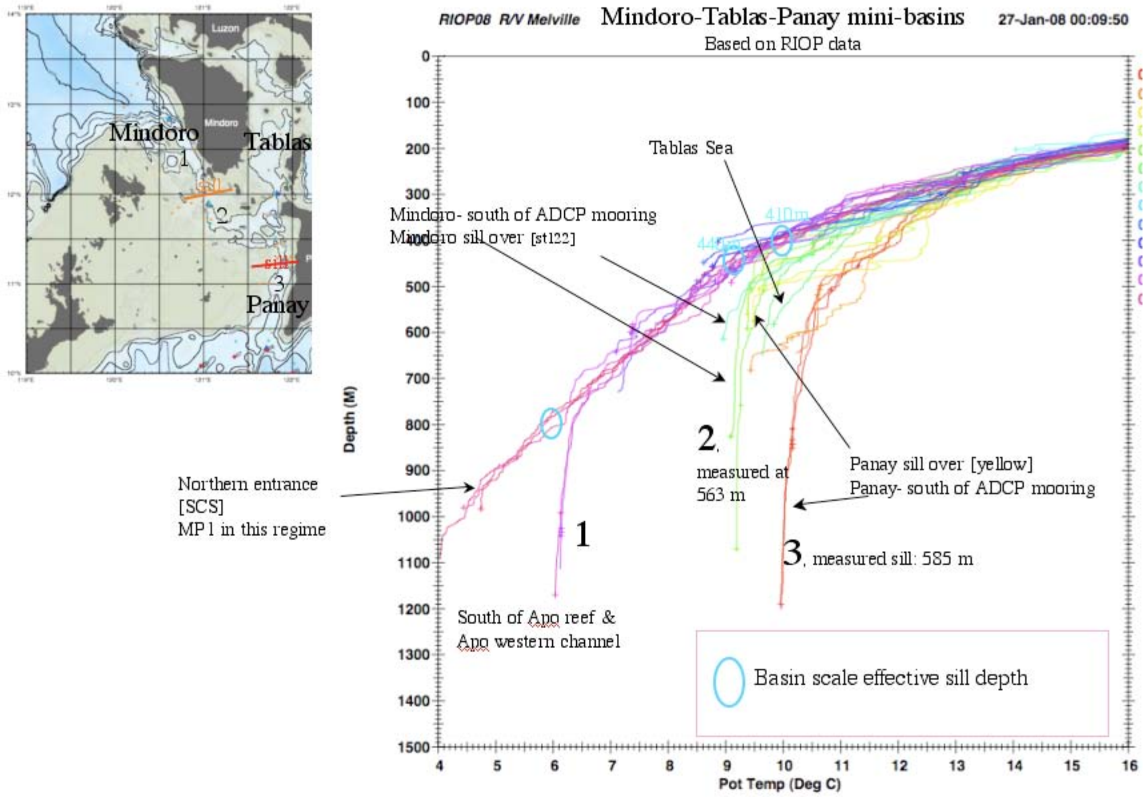

Figure 5 the mini-basins within the Mindoro and Panay Straits are revealed by the temperature profiles.

§ Seasonality: During the Exploratory Cruise of June/July 2007 we observed a transfer of surface water from the Sulu Sea into the South China Sea [SCS]. There was flow from the SCS to the Sulu Sea associated with a salinity maximum [S-max] near ~200 to 250 meters [lower thermocline]. The SCS S-max is found throughout the Sulu Sea, and enters into the Mindanao Sea. The S-max persisted into July 2007, though the southward speed decreased, presumably as a consequence of the maturing summer monsoon. Below 400 m there was more substantial southward flow associated with the overflow into the deep Sulu Sea.

The RIOP08 reveals that during the winter monsoon the surface layer transfer between the SCS and Sulu sea is masked by energetic wake eddies produced by the textured wind stress curl patterns as the NE monsoon winds encounter the mountainous Philippine Islands [Figure 4]. The southward flow at the 200 m S-max drawn from the SCS is evident]Figure 6]. Figure 6a-f offer informative series of profiles derived from the CTD and lowered ADCP, whose discussion would take too much text for this annual report, but as a picture is worth a lot of words, these are offered with few words embedded within the within the figures and their captions.

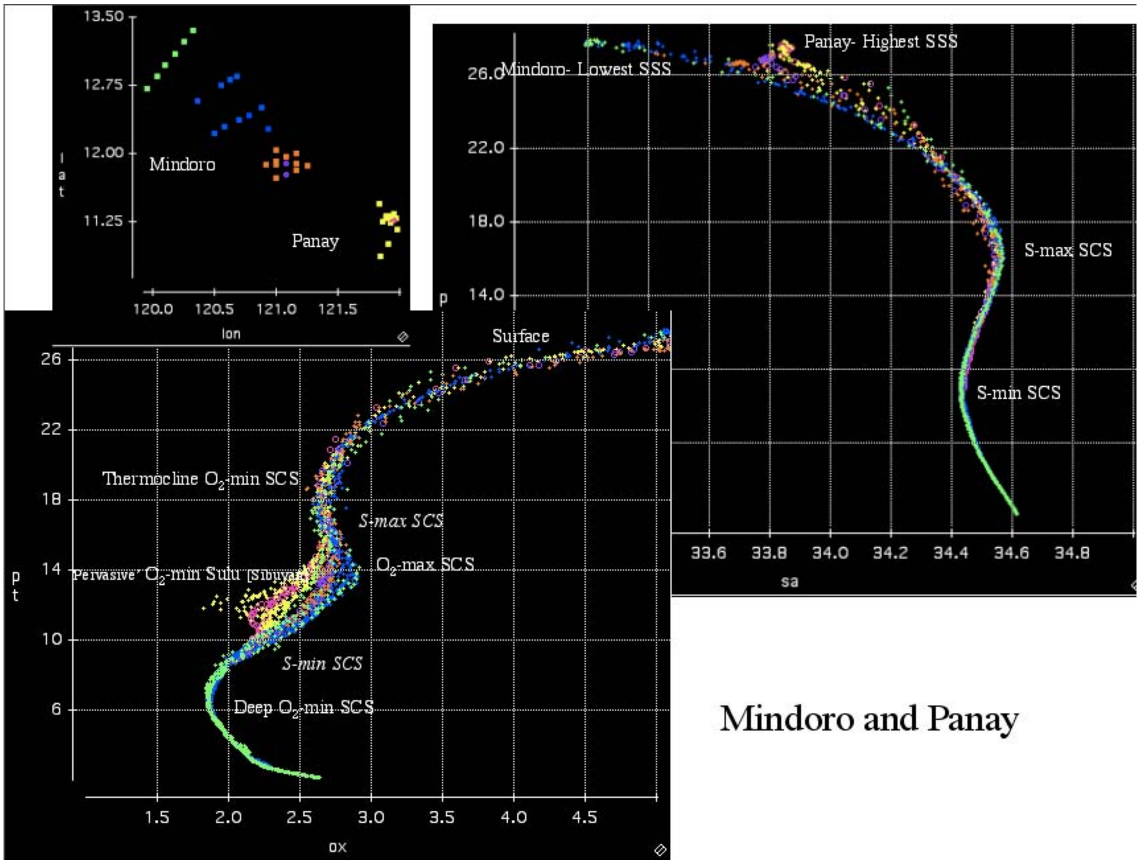

Figure 6a: Potential temperature /Salinity and the Potential temperature / oxygen scatter, color-coded for 4 sub-regions within the Mindoro and Panay Straits, see map insert. The S-max near 16°C is derived from the South China Sea [SCS] as is the S-min at cooler deeper levels. The S-max is what is left of the inflow of Pacific thermocline water via the Luzon Strait into the SCS. The S-min is the North Pacific Intermediate Water, which also enters the SCS via Luzon Strait. The pervasive oxy-min is seen near the 12°C layer.

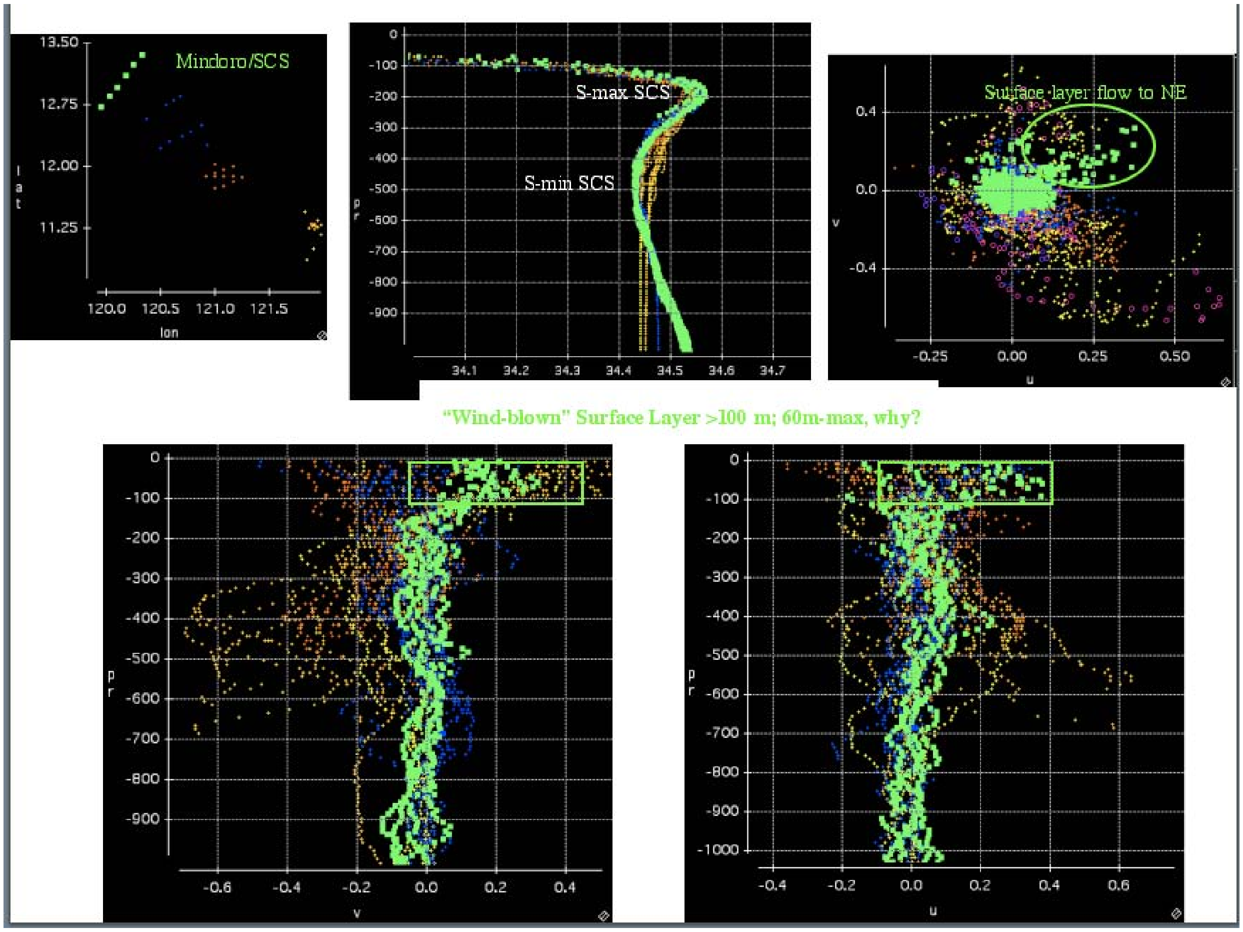

Figure 6b: The northern Mindoro profiles of salinity and of the zonal [u] and meridional [v] flow observed by the lowered ADCP. The u/v scatter is shown in the upper right panel. The surface flow is towards the NE, part of the cyclonic wake eddy characteristic of that region, see Figure 4. Below 100 m the u and v components are less than 0.1 m/s. From 100 to 600 m the flow averages slightly toward the SE, consistent with the movement of the SCS S-max and S-min towards the Sulu Sea. A maximum eastward flow near 400 m is within the SCS derived S-min layer.

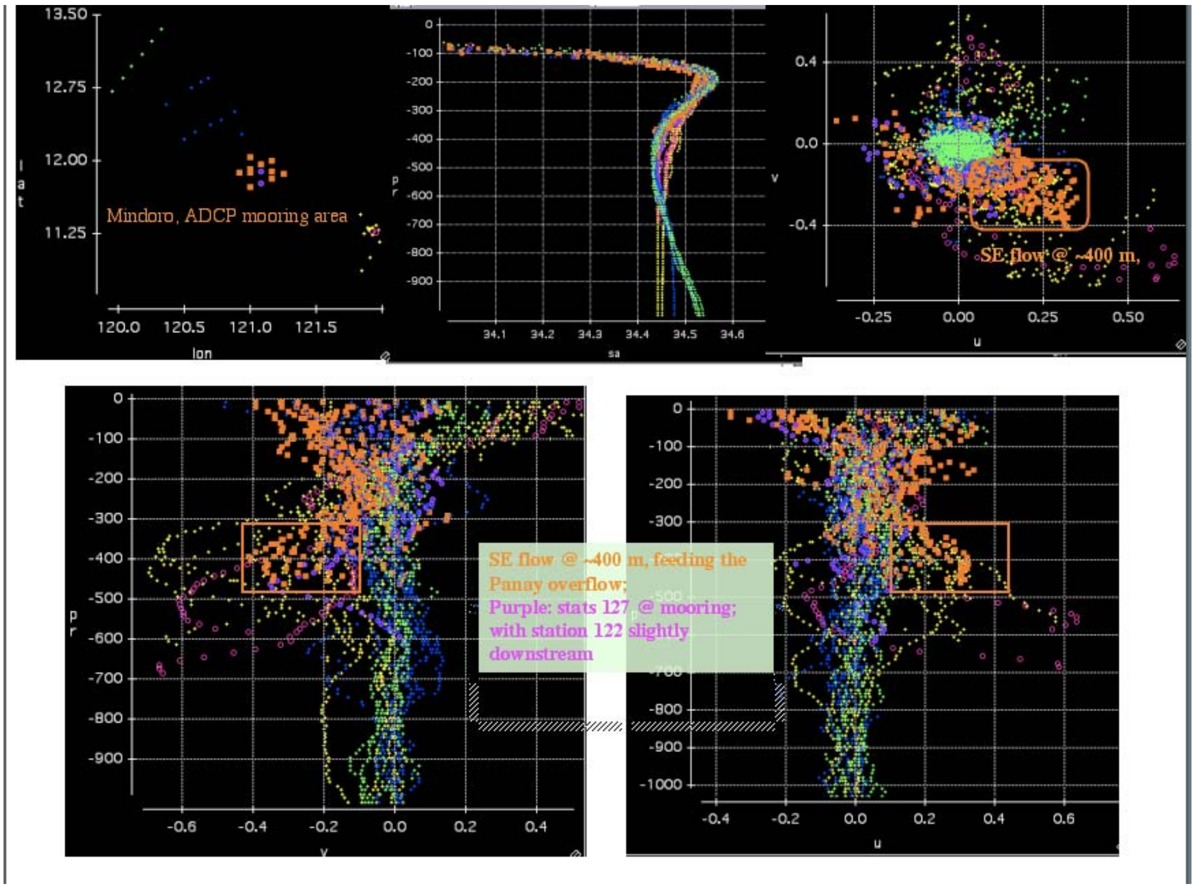

Figure 6c: Mindoro at the ADCP mooring site. The surface flow has a strong component towards the south [though split between to the east and to the west], likely part of the wake eddy off the southern tip of Mindoro [Figure 4]. Strong flow towards the SE is found at 300-500 meters, which feeds the overflow in Panay Strait. This and the overflow to the Sulu Sea is the major aspect of the sub-surface circulation within Mindoro and Panay Straits.

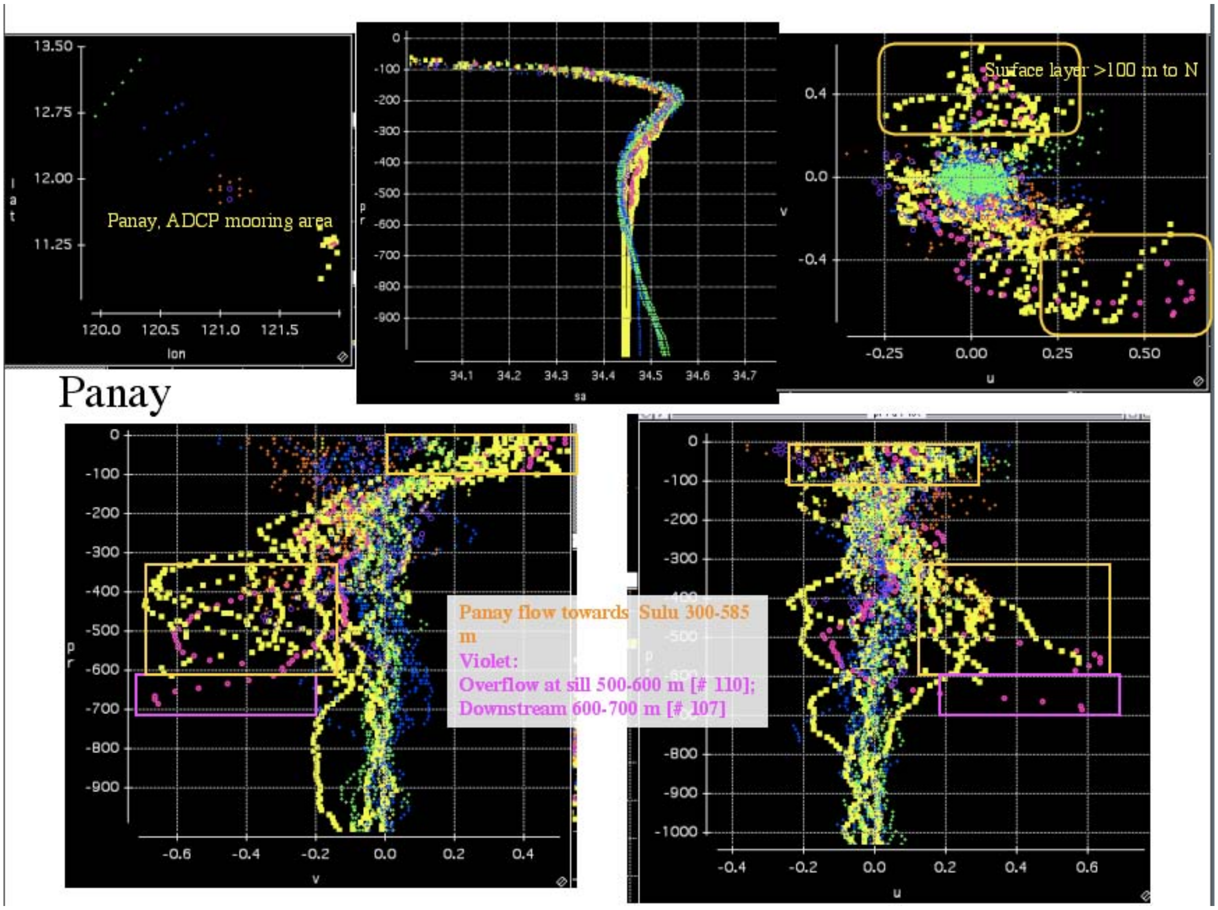

Figure 6d: The Panay Strait at the ADCP mooring site. The surface layer has a strong northerly component, part of a wake eddy formed off he northern tip of Panay. At depth things get interesting, within the vigorous overflow into the Sulu Sea [see report from the Exploratory Cruise]. The flow below 300 m attains values of a knot.

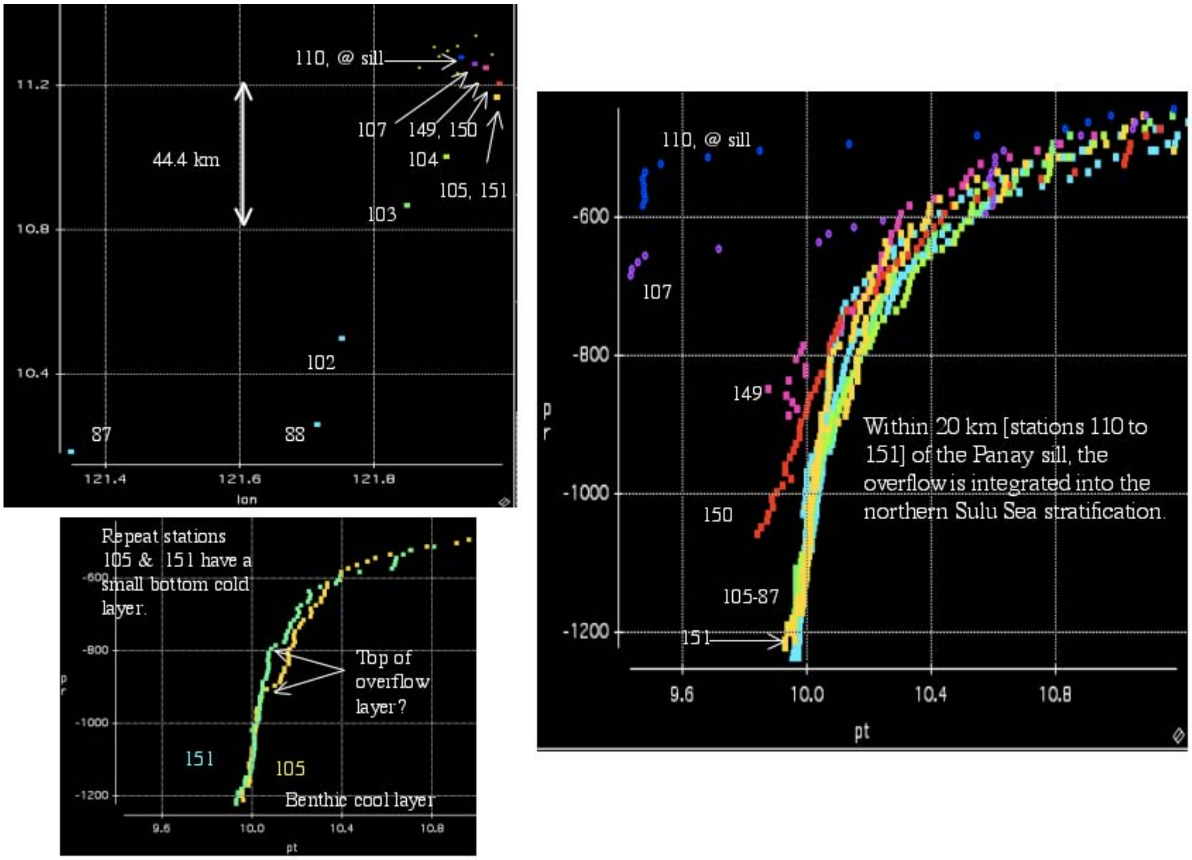

Figure 6e: A sequence of CTD stations from the Panay overflow sill [station 110] downstream towards the Sulu Sea. The attenuation of the cold benthic layer to the ambient water is essentially complete at station 151, only ~20 km south of the sill. This suggests rather energetic mixing of the gravity current with the ambient water.

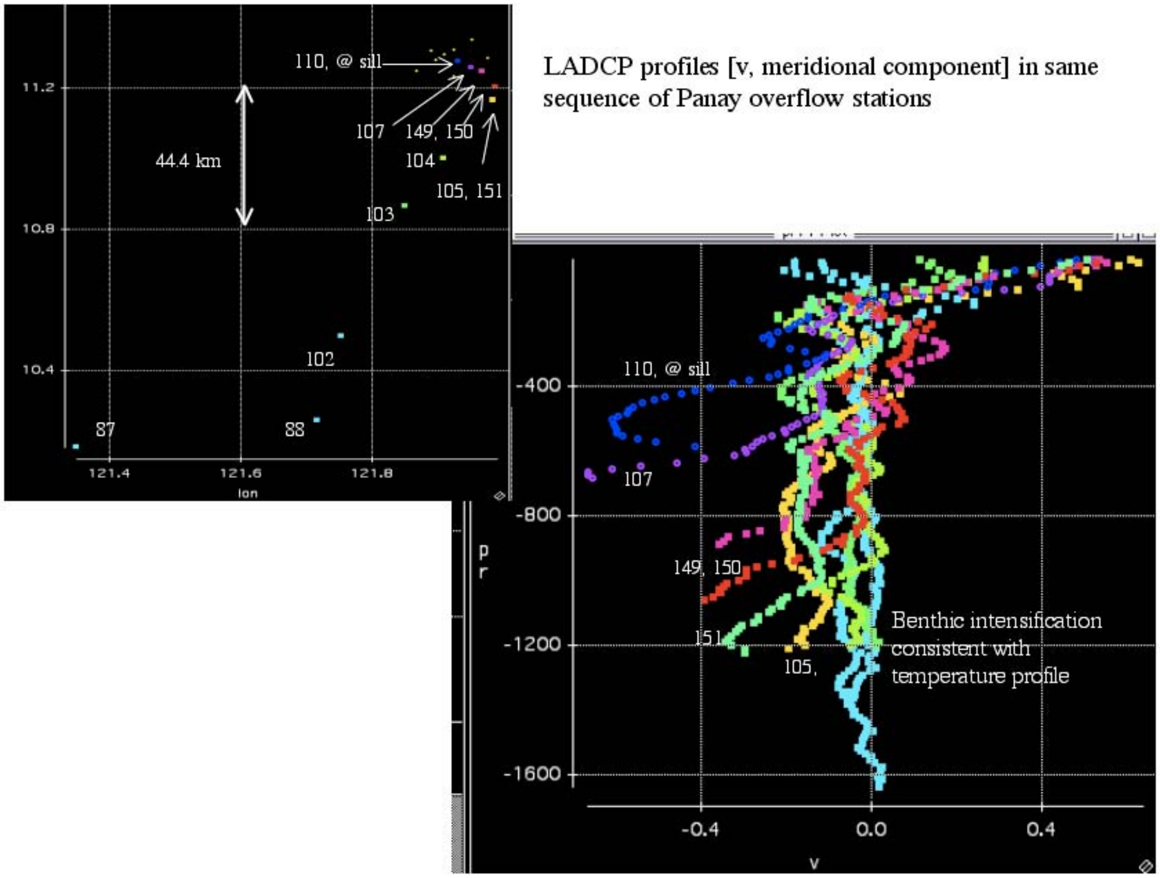

Figure 6f: The meridional speed at the CTD stations shown in Figure 6e. As the temperature of the benthic layer is mixed upward so is the kinetic energy of the gravity current, with the benthic speeds decreasing from ~1 kt to effectively zero in ~20 km.

• Dipolog Strait: The CTD and lowered ADCP profiles reveal the highly sheared circulation system [Figures 7a, 7b]. The schematic of the overturning circulation within Mindanao Sea is shown in Figure 8]. There are 2 systems exchanging water between the Mindanao and Sulu Seas through Dipolog Strait [Figures 7a, 7b]. The upper one is composed of surface outflow to the Sulu Sea, compensated with ~150 m inflow to the Mindanao Sea. This system is akin to an estuary circulation, with Pacific waters exiting the Mindanao Sea within the surface layer. Another exchange system is observed at deeper levels. There dense water overflows to the depths of the Mindanao Sea within the lower ~50 m, with export in the 300-350 m interval towards the Sulu Sea of the displaced resident water. This may be considered as buoyancy driven overturning circulation. Above the confines of the deep channel the flow circulation patterns is tilted across the Dipolog Strait [best seen >200 m in fig 7b], so that the estuary outflow is stronger on the north side, estuary inflow stronger on the south side.

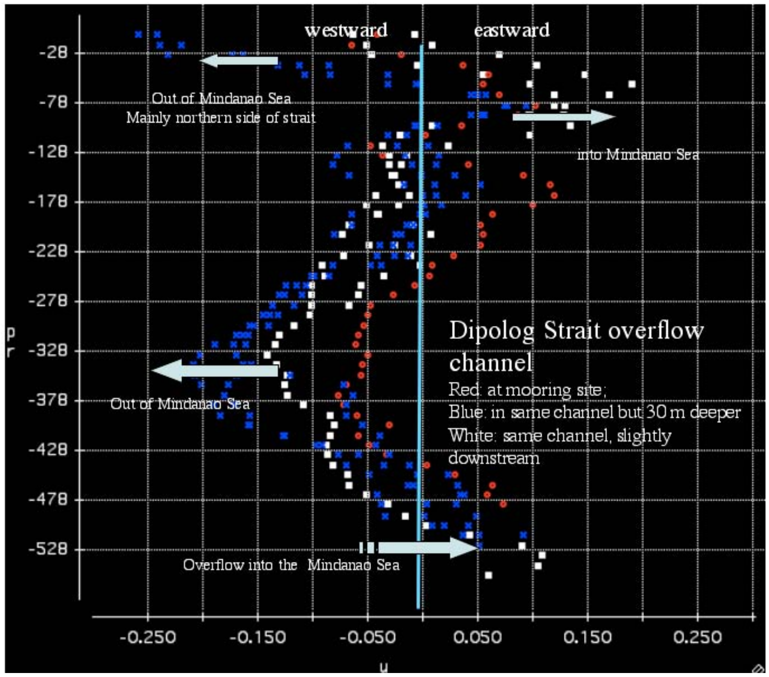

Figure 7a- LADCP profile of zonal flow in Dipolog overflow channel

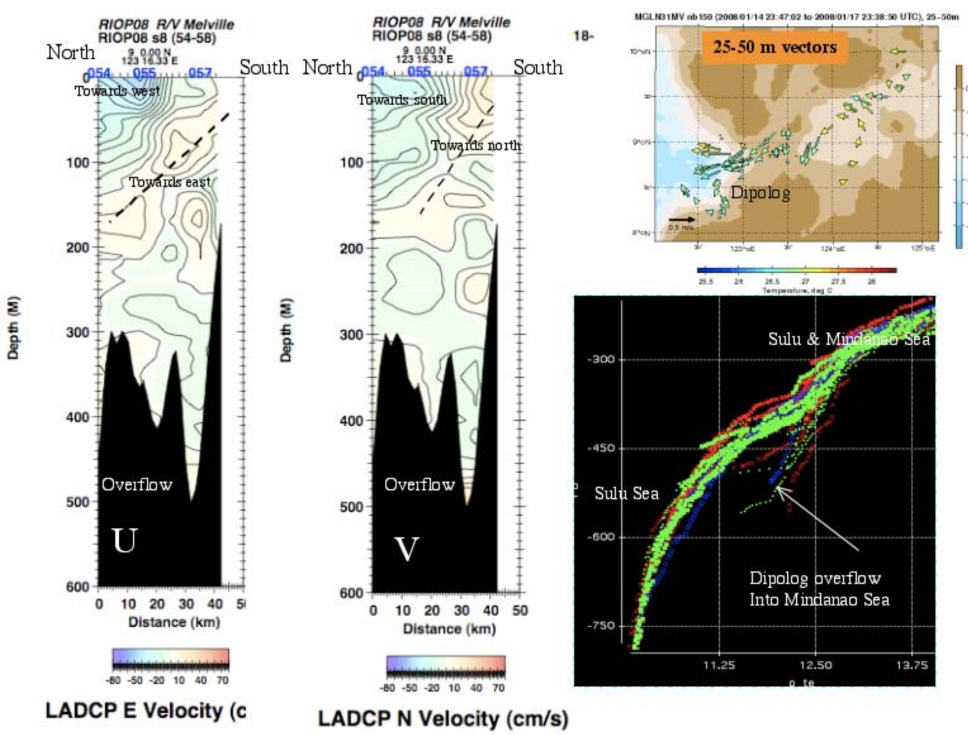

Figure 7b. Left panel: Lower ADCP section across Dipolog Strait. Upper right: hull ADCP measured currents in the 25-50 m layer. Lower right: θ°C profiles at Dipolog and in adjacent Sulu Sea

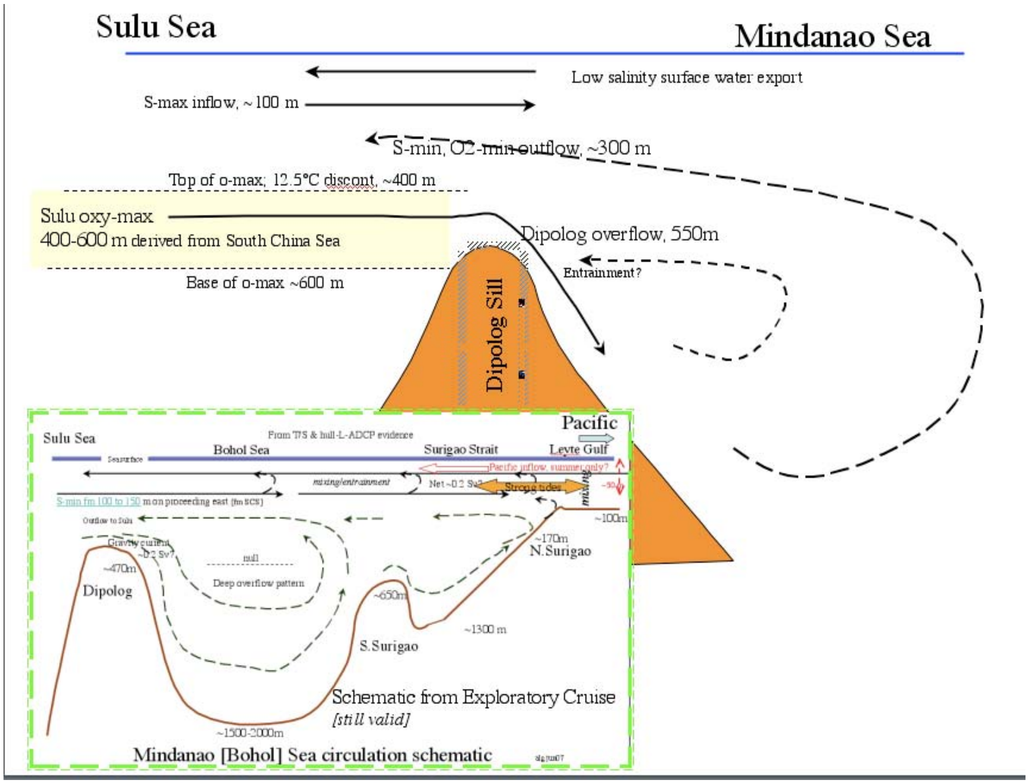

Figure 8 Extension of the Mindanao Sea schematic to the adjacent Sulu Sea.

• Sulu Sea

§ Surface layer circulation: The salinity maximum found in the western Sulu Sea near 150 m is derived from the South China Sea via Mindoro/Panay Straits. At 300 m a weak salinity minimum, with a more pronounced oxygen minimum is derived from the outflow from the Mindanao Sea [the pervasive O_2-min; Figure 9]. The surface circulation in the 'winter' Sulu Sea is cyclonic, though the presence of meso-scale eddies are suggested by the hull mounted ADCP and as shown by the NRL 32° model [figure 10]. At depth, 150 m, the gyre appears to be shifted westward.

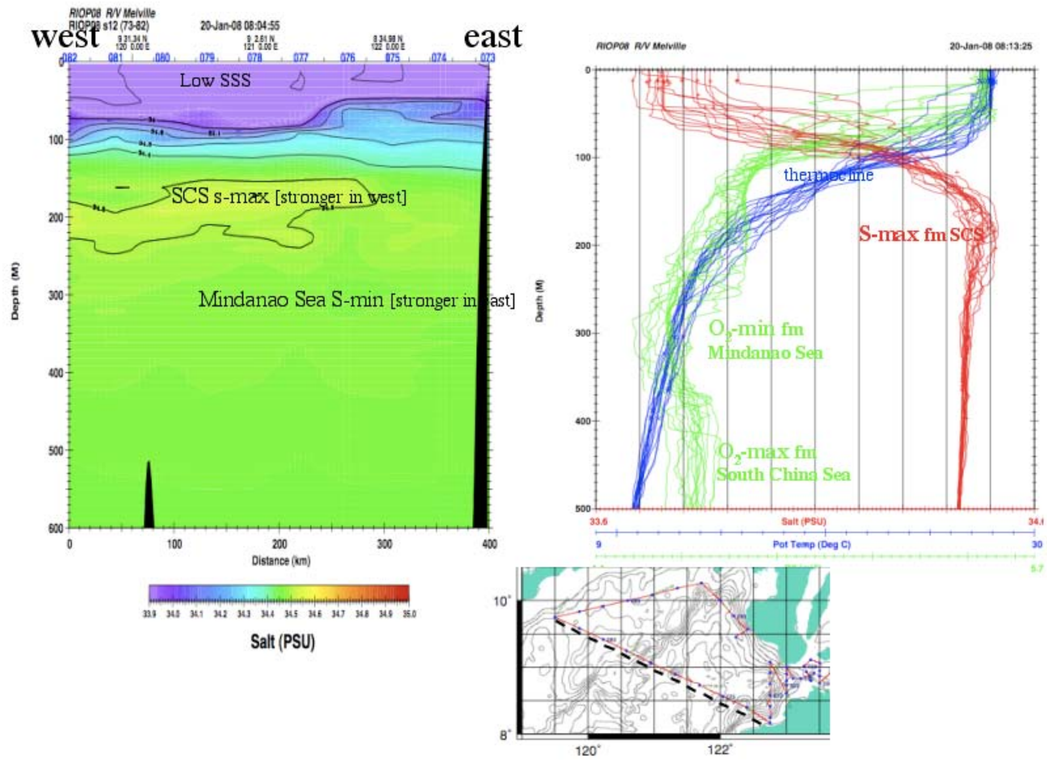

Figure 9 Sulu Sea stratification

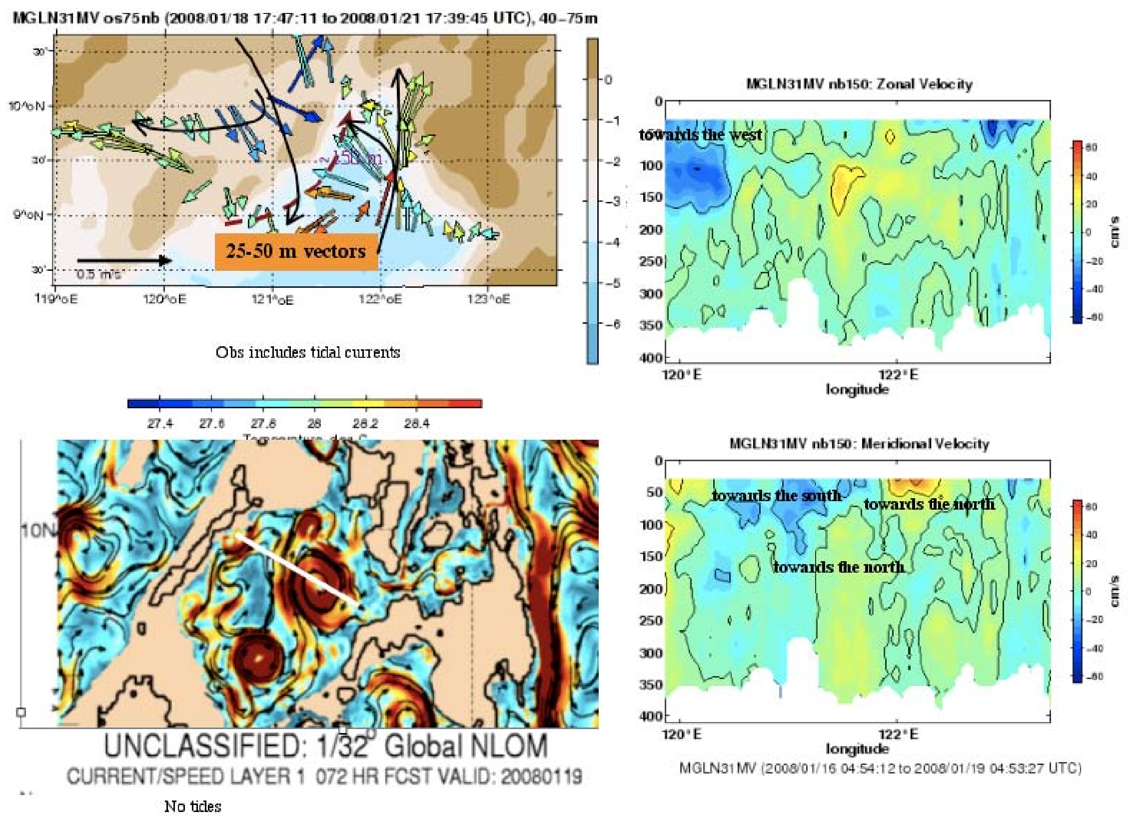

Figure 10 Sulu Sea circulation. Upper left panel is from hull ADCP at 0200L 22 Jan 08

• Deep Sulu Sea Ventilation Puzzle [Figures 11, 12 and 13]: Below 1000m the Sulu Sea is nearly adiabatic though it warms slightly from a θ-min near 2800 m, but yet salinity increases with depth, oxygen decreases with depth. For a single source for the water within the isolated confines of the Sulu basin one would expect both conservative properties of potential temperature and salinity to be homogeneous, oxygen, a non-conservative property would be expected to be reduced]. Geothermal heating would boost the temperature a bit, so a source somewhat cooler than the resident deep water is needed.

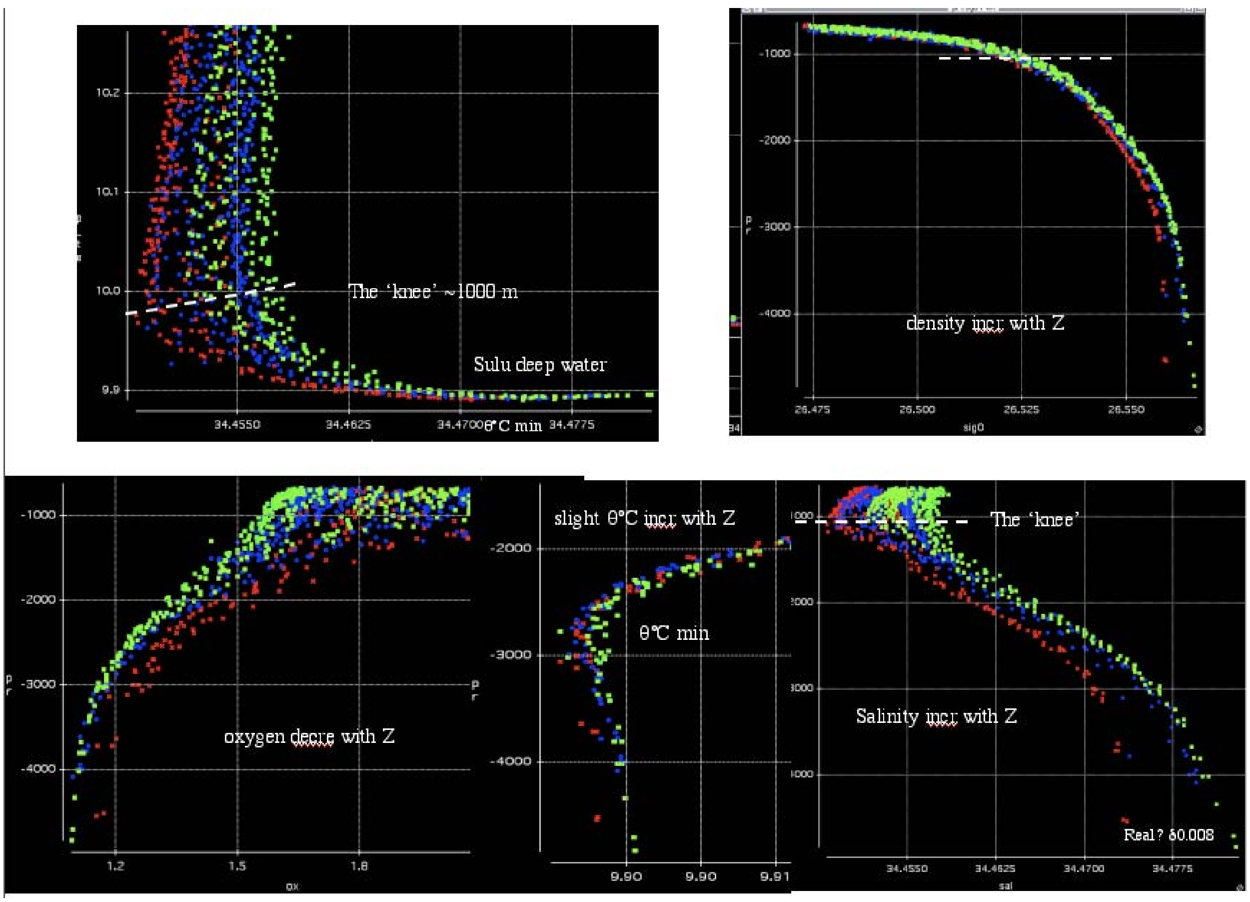

Figure11a Deep and bottom waters of the Sulu Sea.

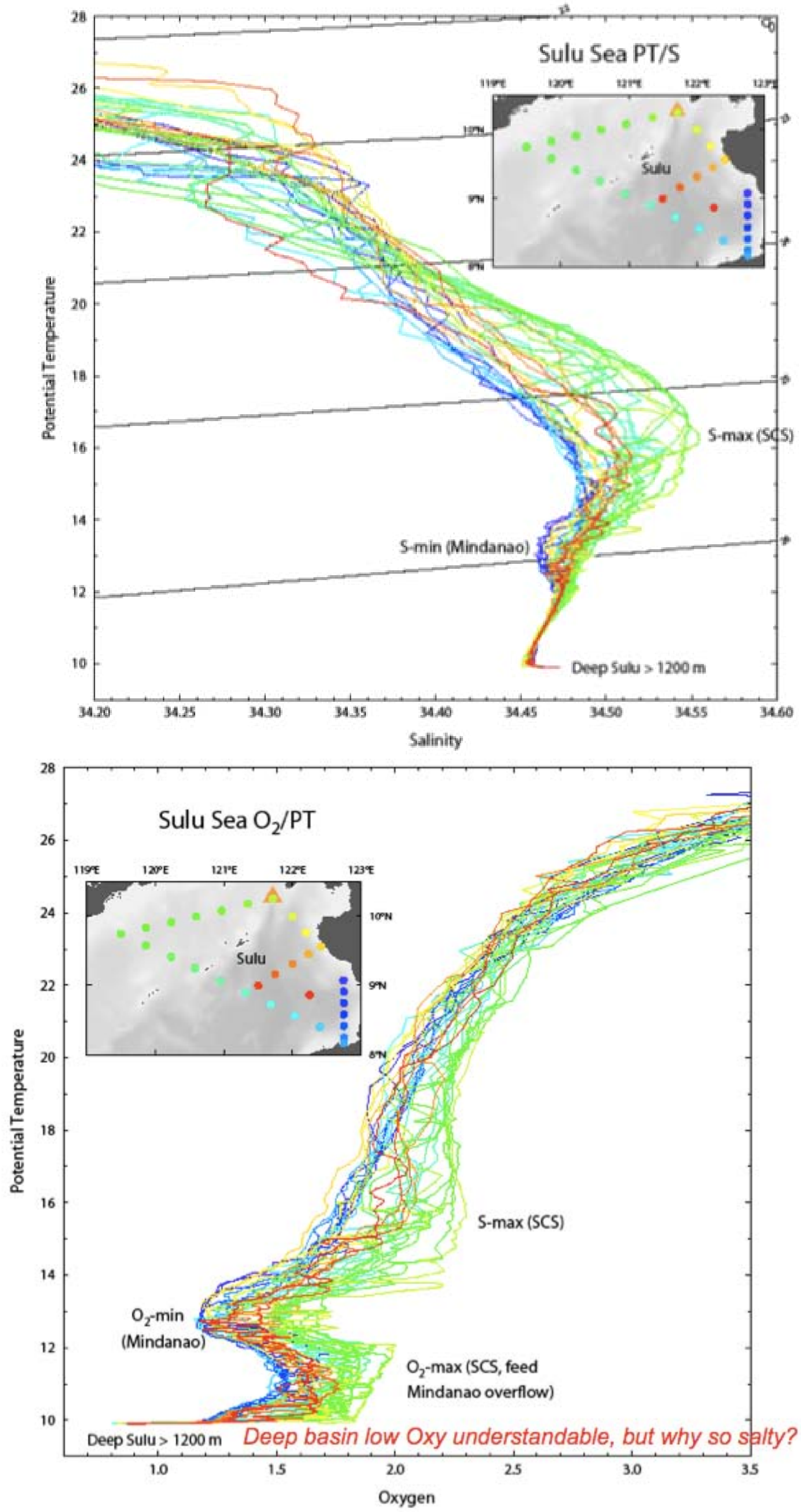

Figure 11b T/S and T/Oxy of the deep Sulu Sea water column.

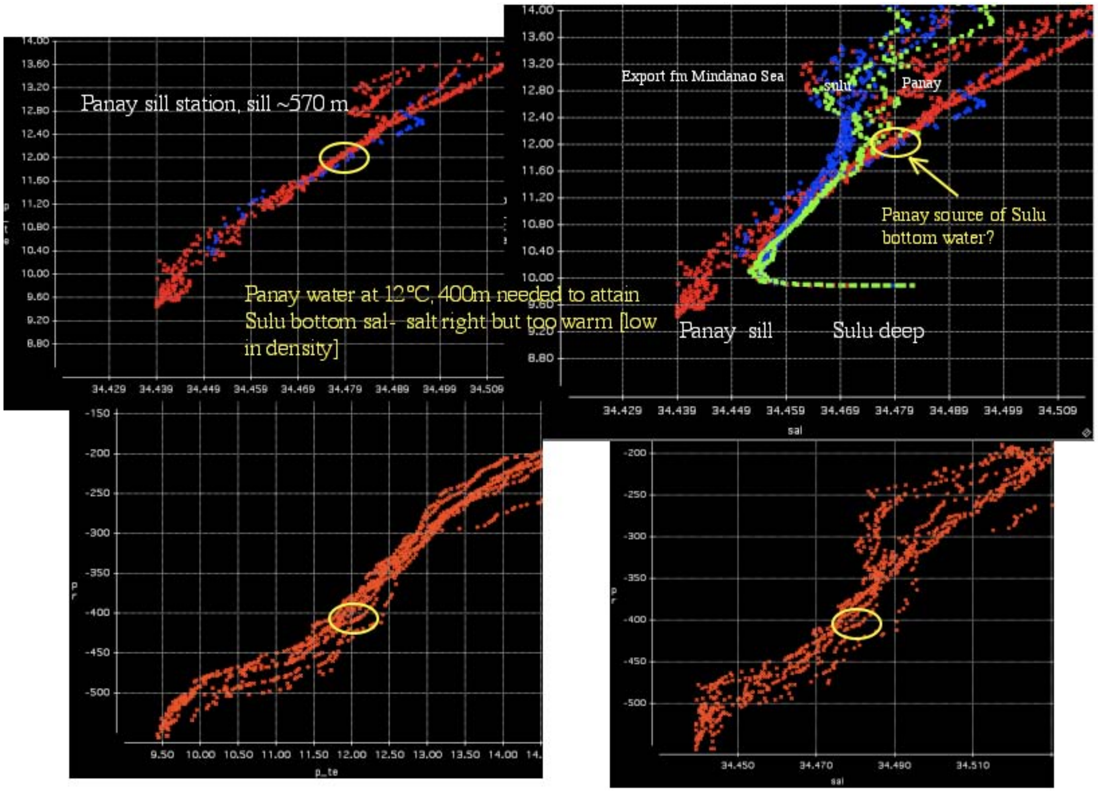

Figure 12 Panay overflow stations [red and blue], and the Sulu Sea deep water [green]. The yellow oval marks the water type that has the salinity to account for the Sulu Sea bottom water, but its temperature is too high to serve as the source water.

The Deep Sulu puzzle: What is the cause of the well-stratified water column within the Sulu Sea well below the Panay sill depth?

The Sulu bottom water is 34.48 and 9.8°C. The Sulu bottom water source can't come from the north, from the South China Sea via Panay - to get the right salinity from Panay would be coupled to water too warm, around 12°C, to be the source of the Sulu bottom water. Using 1993/94 data [Figure 13] in the Sulawesi Sea [the sea south of Sulu] the right water is found at a depth of 400m . The Sulu Solitons are produced just east of Pearl Bank at 5.9°N and 120°E, in a 340 meter channel. The deepest sill connecting the Sulawesi to the Sulu may be south of the Pearl Bank at the Sibutu Passage, which may be closer to 300 m.

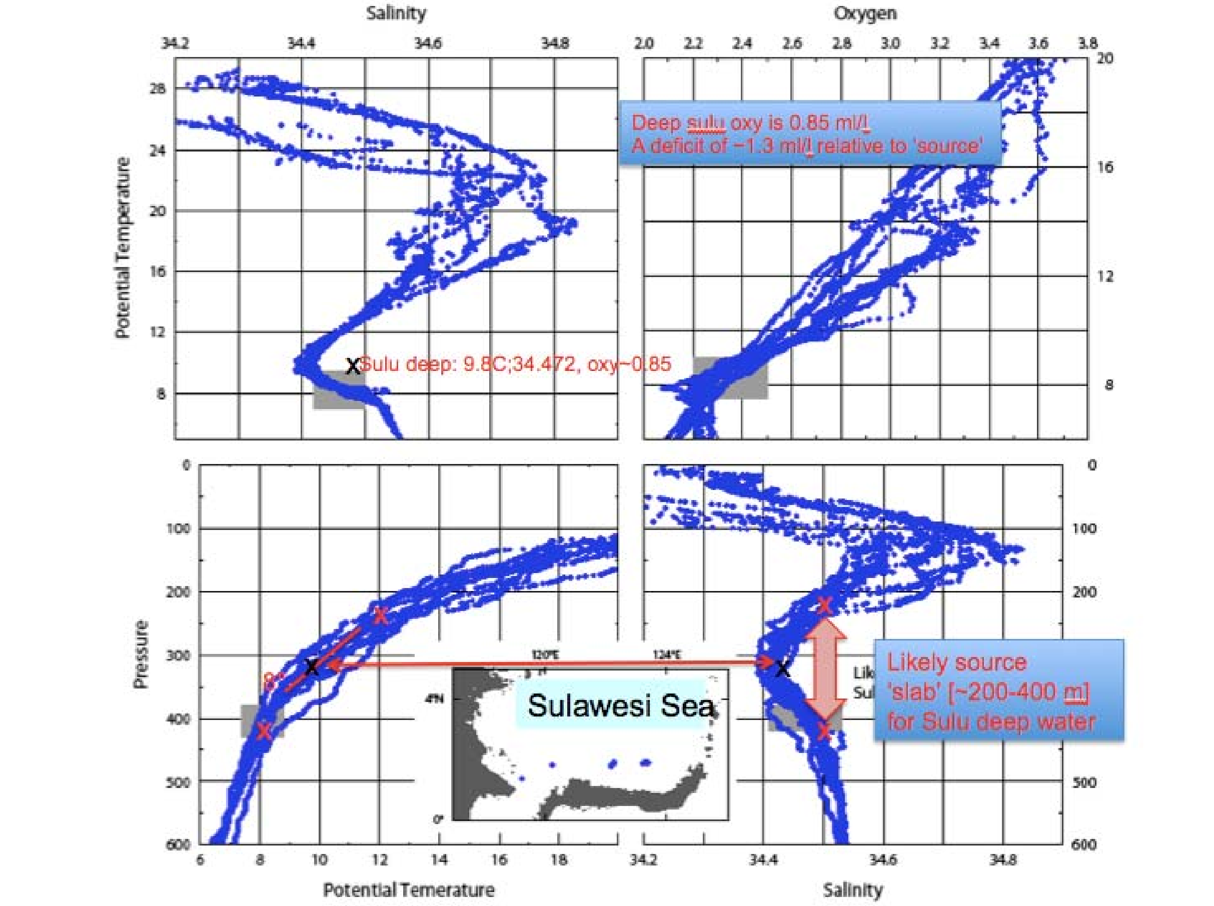

Figure 13 CTD stations from the Sulawesi Sea. The yellow oval marks the properties that can be the southern source of the Sulu Sea bottom water.

Hypothesis: bursts of sub-sill water make it over the Pearl Sill from the Sulawesi Sea at Spring tide when the Solitons are produced. See Schematic, figure 14

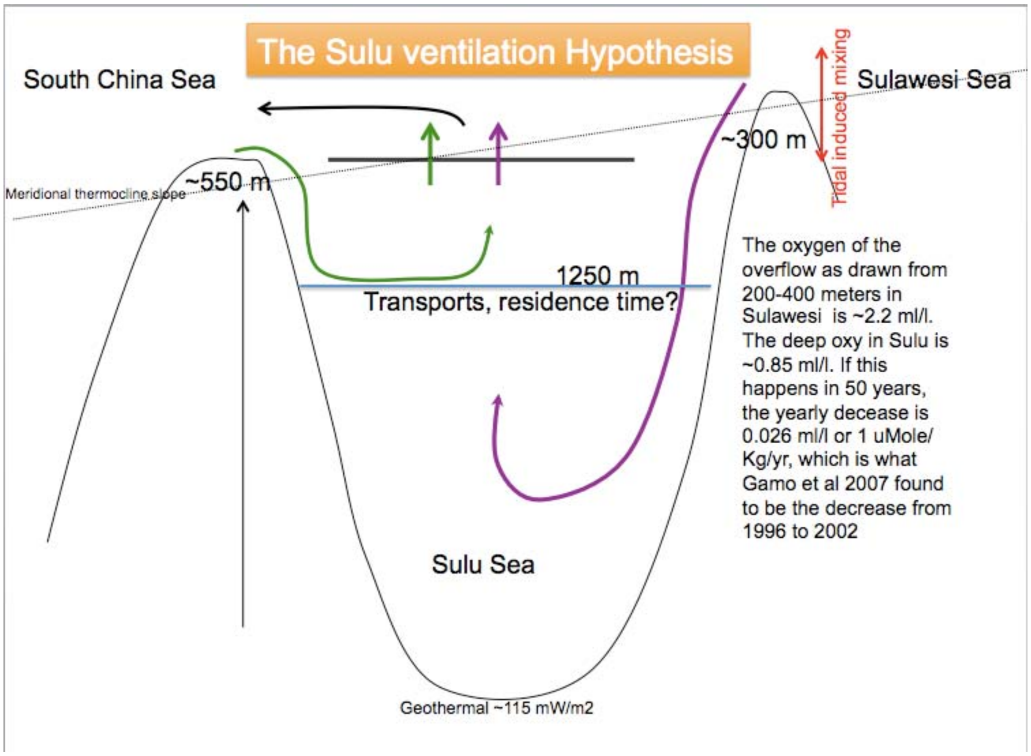

Figure 14: Schematic of the overflow pattern into the deep Sulu Sea. The large scale shallowing of the thermocline from the subtropics to the tropics is what enables the Sibutu Passage to compete with the deeper Panay Strait sill.

It is proposed that the deep Sulu Sea has two 'competing' sources of ventilation**:**

• Panay allows South China Sea water of 9.5°C, 34.44 to enter the Sulu Sea at 570 m; this water forms the deep layers within the Sulu Sea.

• Sibutu Passage allows water of 8 to 9°C, 34.48 to enter the Sulu Sea at 400 m to get into the Sulu from the Sulawesi.

The Panay is not the only source for ventilation of the deep Sulu Sea- residence time estimates derived from the Panay over flow would be too long. Geochem and paleo analysis of Sulu data assuming a single ventilation source from the north may be wrong.

IMPACT/APPLICATIONS

The PhilEx cruises provide information for addressing the PhilEx objectives, by resolving the stratification and circulation patterns inder varied forcing conditions, within the complex topography of the Phillipine Seas. The resultant numerical model, honed by observations, and the enhanced understanding of the oceanography of the Philippine waters to be produced by the PhilEx program will have a multitude of applications in managing marine resources and the marine environment of the Philippines, as well as for issues of marine safety and prediction of marine pollution dispersion.

TRANSITIONS

None

RELATED PROJECTS

none

REFERENCES

None

PUBLICATIONS

None

PATENTS

None